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Australites from Hampton Hill Station, Western Australia

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Abstract

The largest known concentration of australites (Australian tektites) was on Hampton Hill pastoral station, Western Australia. Nearly 22 000 of them have been classified morphologically according to a "binomial" scheme based upon two views of the australite when oriented in ablation flight: the classification scheme is described in detail. Comparisons have been made with some other localized occurrences but their usefulness is limited by differences in definitions and bias in samples. Minor studies were made of the distinction between oval and boat shapes, the derivation of "conical" cores, and weight distribution amongst whole australites.

Introduction

This paper is an account of the australites collected on Hampton Hill Station. The western boundary of the station is 9 km east of Kalgoorlie and the homestead is a further 18 km east (Fig. 1). The property is owned and operated by Mr C. B. C. Jones and family. It includes the abandoned gold-mining centre of Bulong, once a considerable town—indeed, a municipality—and the sites of the former small mining townships of Kurnalpi, Boorara and Golden Ridge. It includes also the complex lake system comprising Lake Yindarlgooda, its north-easterly extension sometimes known as Lake Lapage, and the yet further extension shown on some maps as Cooragooggine Lake. Thus the australites attributed variously to Bulong, Kurnalpi, Lake Yindarlgooda and Lake Lapage qualify for consideration here.

There are well over 22 000 australites from Hampton Hill Station in collections. The principal units examined were the Hampton Hill components of the various Jones family collections totalling 14 155 and of the Tillotson family collections totalling 7 478. Small numbers in the British Museum (Natural History), National Museum of Victoria, South Australian Museum, Western Australian Museum and W.A. School of Mines totalling 294 were also examined. A few hundred others, principally in the Smithsonian Institution, American Museum of Natural History and the private collection of Mr P. J. Simmonds, but also as small representations in a number of official and private collections, were excluded from this study for various reasons. It is unlikely that the excluded specimens, which constitute about 2% of those known to be in collections, would affect significantly the results obtained.

Hampton Hill Station contained the largest known concentration of australites. The only other area which has yielded a comparable number of specimens is that spanning part of the South Australia-Northern Territory border. From that area have come the Kennett collection (7184) and the Finke collection (1811), both of which are in the South Australian Museum. The Finke collection is a selection from a large number visually estimated by Ms J. M. Scrymgour as 10 000-12 000. Thus a total number in the order of 17 000 to 19 000 (exclusive of minor representations) is known to have been collected from that region, but only about half of them are in collections which are available for study. The total number is comparable with that from Hampton Hill Station but there is a major difference in the areas involved. It can be estimated from the statements of Mr Kennett quoted by Fenner (1940: 307) and the statements of Mr McTavish of the former Apatula Mission at Finke on the occasion of sale of australites to the South Australian Museum (J. M. Scrymgour *pers. comm.*) that the adjoining and partly overlapping provenances of the Kennett and Finke collections have a total area in the order of 22 000 km². Baker (1956:65) gave closely the same figure for the provenance of the Kennett collection alone. Hampton Hill Station has little more than one seventh of that area; moreover, though australites were widely distributed, most located specimens were found on only a fraction of the station. The Hampton Hill australites would have been in the order of 20-30 times more concentrated than those of the South Australia-Northern Territory border region.

Australites in the Tillotson collections are specifically located and a "centre of occurrence" could be calculated by weighting the geographical co-ordinates of each item in the collection by the number of specimens in the item (Cleverly 1976: 223). Additional collecting since 1976 has made it desirable to recalculate the "centre of occurrence" as 121°56.3'E., 30°39.2'S., a slight modification of the earlier result. The centre is within a broad, boomerang-shaped area marginal to the lakes (Fig. 1) within which more than 97% of the Tillotson specimens were found. The belt extends from a point south-east of Bulong clockwise through Taurus, Lake Penny, northern Lake Yindarlgooda, Jubilee and Lake Lapage, to the vicinity of Kurnalpi and occupies closely one quarter of the area of the station. Most of the specifically located specimens of the small collections

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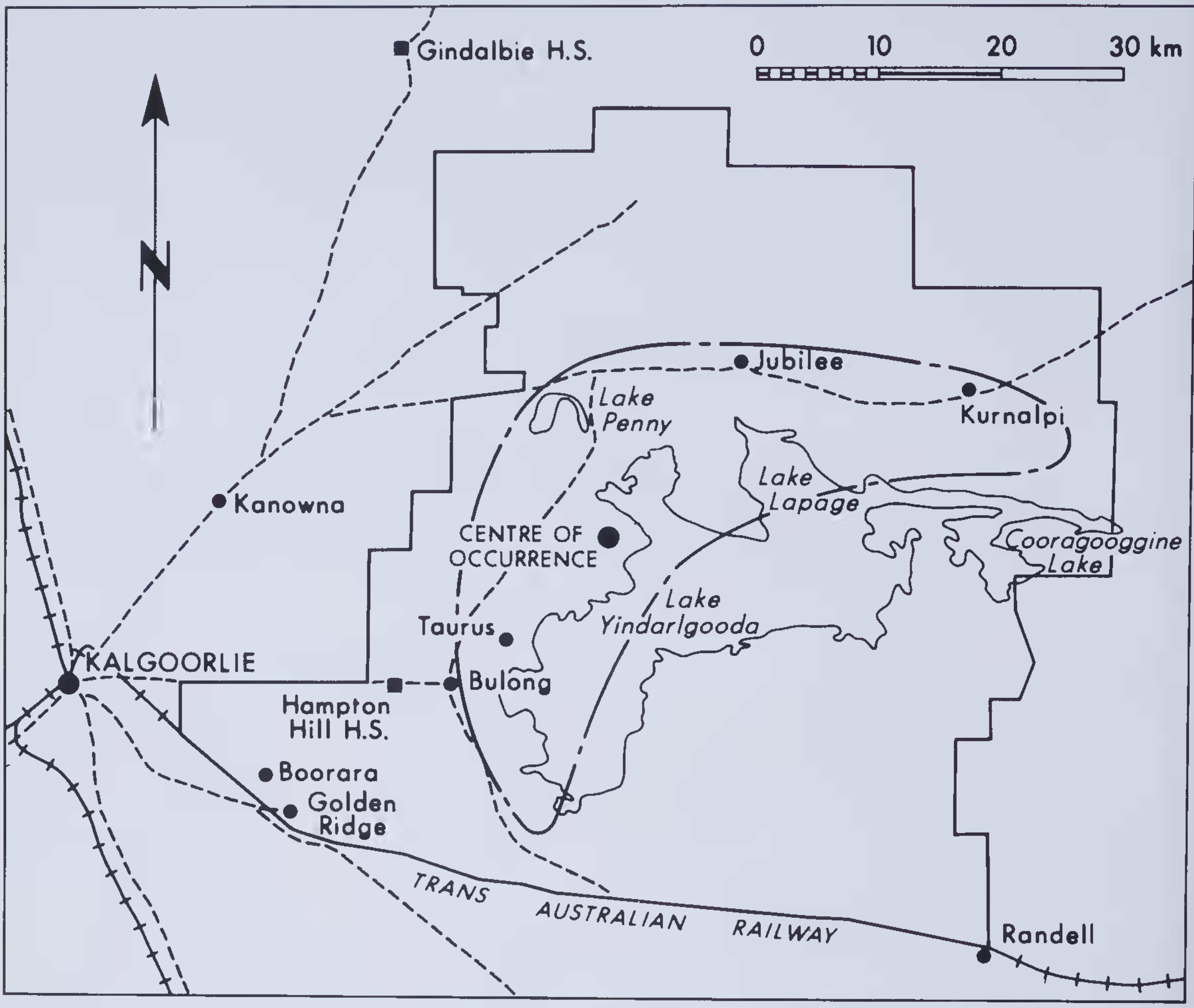


Figure 1.—Hampton Hill Station (firm line boundary) showing the boomerang-shaped area around the lakes within which more than 13 000 australites were found.

which were examined are also from within the boomerang-shaped area. Nearly all the 5 339 specimens in the collection of Mr and Mrs B. C. Jones were found within the same area as a highly concentrated occurrence a few hundred metres diameter at approximately 121°57'E., 30°41'S. This real feature of the shower was near the edge of the lake in the general vicinity of Rocky Dam and only about 3km distant from the calculated "centre of occurrence". It was almost certainly identical with the small area known later as "Moriarty's Patch", from which a Kalgoorlie lapidary and mineral dealer obtained many australites. The Tillotson collections also contain 507 from the vicinity of Rocky Dam and Moriarty's Patch but the best represented area in their collections is somewhat further south-west in the general vicinity of Taurus, from which they obtained nearly 3 000 specimens.

The boomerang shape of the concentration may have originated in this manner. The australite shower was very uneven in density (Fenner 1935, McColl and Williams 1970). One patch of greater than average abundance of radius a few tens of kilometres was centred round the small area of extreme abundance collected by Mr and Mrs B. C. Jones. Subsequent modification of the shape depended on peculiarities common to many lakes in this part of interior Western Australia. The lakes tend to have rocky western and northern shorelines of relatively simple outline and highly complicated eastern and southern shorelines where there is a complex of gypseous dunes, innumerable small basins, inlets and billabongs. The lake basins are visualized as migrating as the result of active pediplanation on the first type of shoreline and aggradation on the other. On the north-western side, small intermittent streams such as Magnesite Creek brought australites down towards the lake and onto the numerous flat alluvial fans which extend out over the exposed or thinly concealed rock pediment. Because the shoreline is convex to the north-west, the zone of concentration is similarly curved. On the south-eastern side, australites were buried under the encroaching dunes. The western and northern shores have been the more readily accessible to collectors until four-wheel drive vehicles became generally available in recent years. This circumstance may have exaggerated the natural difference in australite abundance between the north-western and south-eastern sides.

The only located items of any size from outside the boomerang-shaped concentration are 196 australites in the Tillotson collections from the east side of the extreme south end of Lake Yindarlgooda and 461 in the J.L.C. Jones collection from "eastern" Lake Yindarlgooda. Both items include some of the best examples of australites with V-grooves (Fig. 6) discussed in the last section of this paper. The precise locality of the J.L.C. Jones material—suspected to be close to or identical with the Tillotson locality—was not disclosed. Thus the area of concentration as shown in Fig. 1 should perhaps be modified or extended slightly to include the southern tongue of Lake Yindarlgooda.

The remaining nearly 9 000 specimens in the Jones collections are unlocated except insofar as they are from Hampton Hill Station, but it is known that many of them came from the lakes, if not from the area of concentration.

The proportion of spurious specimens detected was rather higher than usually found in collections. Most are small, worn, almost black fragments of ultramafic rock and are visually deceptive except that their thin edges show a distinctive green (serpentine) colour in transmitted light. Their source is a broad band of ultramafic rock forming the western margin of Lake Yindarlgooda. Of the 22 087 specimens examined, 160 (0.7%) were spurious, so that the genuine australites numbered 21 927.

Morphological classification.

A "binomial" system of classification has been used (Table 1) based upon two views of the australite whilst it is in flight orientation with the line of flight imagined to be vertically downward. The system allows for 46 shape types. Two additional types—"conical cores" and "aberrant forms" are recognised. The total of 48 types is more than in any classification except that of Fenner (1934) but is believed to be appropriate for a group of australites three times as numerous as any previously reported upon in this way. The classification is largely genetic. A brief statement of the author's understanding of the development of australite shapes therefore follows, but it is not necessary that the reader subscribe to these beliefs in order to use the system.

In consequence of some major impact event, a rebound jet of melt was dispersed as millions of small masses with high velocity. These masses assumed shapes approximating to the equilibrium shapes appropriate to their rates of rotation and retained those shapes during cooling to form the primary bodies. Subsequently, the resulting cold solid bodies of glass encountered the earth's atmosphere and because of a combination of very high velocity, high symmetry of the shapes and downward direction of flight, most of them adopted stable orientations relative to their flight paths; some had slight axial wobbles or other instabilities. Frictional melting with ablation stripping of the melt and other aerodynamic (secondary) processes modified the shapes of the primary bodies to form the secondary bodies which were decelerated to the very modest velocities of free fall. Some secondary bodies may have been broken on landing but weathering and erosion processes during terrestrial residence have been much more important contributors to their present shapes. The two shape factors used in classification will now be considered.

(a) Shape seen when looking along the flight path.

Though conventionally referred to as the "shape" it is only the profile which is used. It could thus be either the rear (posterior) or the front (anterior) view. If looking downward at the australite in vertically downward flight, the rear view is the plan view or "plan aspect" of Baker and Cappadona (1972). The shape is closely dependent upon the form of the primary body and the orientation adopted relative to the line of flight when it encountered the atmosphere. The author's views of those two things are as follows:—

Spheres The form adopted by non-rotating masses of melt was the sphere. This was the commonest of all primary shapes. Orientation in ablation flight was decided initially by the chance position at atmospheric encounter, but as soon as some ablation stripping had occurred from frontal surface, forces came into play ensuring the subsequent stable orientation relative to the flight path (Chapman *et al.* 1962: 16 *et seq.*).

Oblate spheroids Slowly rotating masses adopted a shape approximating an oblate spheroid with the short axis as the axis of rotation. They oriented in ablation flight with the short axis parallel to the flight path. Certain other orientations which are sometimes figured would have the aerodynamic centre in front of the centre of gravity and would not therefore be stable. The rotation of these and other bodies was usually damped out during atmospheric encounter or was reduced to no more than a slight axial wobble. All sections normal to the flight path were circular. The protected posterior surface of ablation flight, the only remnant from which the form of the primary body can be judged, is only occasionally sufficiently well preserved or large enough for a distinction to be made from the sphere (Chapman and Larson 1963: 4334, Cleverly 1974: 69).

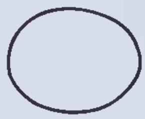
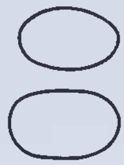
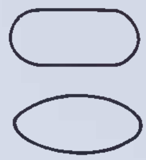
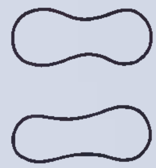
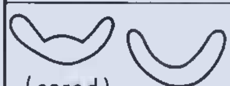
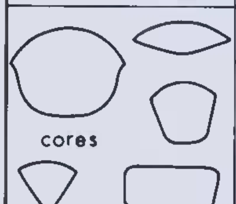
Prolate spheroids More rapidly rotating masses of melt became elongated normal to the axis of rotation, assuming shapes approximating to prolate spheroids or, more correctly, triaxial ellipsoids, though it is only in the largest cores or exceptionally well preserved specimens that departure from circularity in sections normal to the length can be detected in the remaining short arc of primary surface (Cleverly 1979a). They oriented with the longest axis (or two longer axes) normal to the flight path and the shortest one parallel to it. The principal section normal to the flight path was either bluntly oval or more narrowly oval or parallel-sided with rounded ends in the sequence of higher rates of rotation and decreasing numbers of bodies. In some instances, melt flowed unequally towards the ends and the resulting body therefore tapered towards one end.

Dumbbells In yet more rapidly rotating masses, migration of melt towards the ends was sufficient to cause development of a waist. These bodies oriented with the longest axis normal to the flight path and the shortest one (*i.e.* axis of rotation) parallel to it. Sometimes the outward flow of melt was not evenly directed, resulting in gibbosities of unequal size. Such bodies are conventionally referred to as asymmetrical dumbbells though the asymmetry is usually only in respect of the ends, high symmetry being present relative to the other principal planes. The asymmetrical dumbbells oriented with the length off the normal to the flight path, the heavier end inclined forward into the pressure at an angle dependent on the degree of inequality (Chapman *et al.* 1962: 19).

Apioids A few masses rotated sufficiently rapidly for the waists of dumbbells to thin to disappearance yielding two bodies approximating to apioid shape. As they were no longer held together in a rotating system, they presumably flew off tangentially. The largest ones with the longest liquid lives may have made progress towards blunter or even spherical shape. They oriented in ablation flight with the main body forward and the tail obliquely backward, the angle of obliquity depending upon the degree of tapering of the shape.

Table 1

Shape names for australites*

Rear (plan) view → / Side or end view (elevation) ↓	 round	 broad oval $4/3 \geq L/W > 1$	 narrow oval $2 \geq L/W > 4/3$	 boat $L/W > 2$	 (asymmetrical) dumbbell	 teardrop
 flanged form	button	flanged broad oval	flanged narrow oval	flanged boat	flanged (asymmetrical) dumbbell	flanged teardrop
 (cored) disc or plate	(cored) disc	(cored) broad oval plate	(cored) narrow oval plate	boat-plate		(cored) teardrop-plate
 (cored) bowl	(cored) round bowl	(cored) broad oval bowl	(cored) narrow oval bowl	boat-bowl		teardrop-bowl
 canoe form	–	broad oval canoe	narrow oval canoe	boat-canoe	(asymmetrical) dumbbell-canoe	–
 indicator type I	round indicator I	broad oval indicator I	narrow oval indicator I	boat-indicator I	(asymmetrical) dumbbell-indicator I	teardrop-indicator I
 lens form	lens	broad oval lens	narrow oval lens	boat-lens	(asymmetrical) dumbbell-lens	teardrop-lens
 indicator type II	round indicator II	broad oval indicator II	narrow oval indicator II	boat-indicator II	(asymmetrical) dumbbell-indicator II	teardrop-indicator II
 cores	conical cores: (conical) round core	conical cores: (conical or wedged) broad oval core	(wedged) narrow oval core	(wedged) boat-core	(wedged) (asymmetrical) dumbbell-core	(wedged) teardrop-core

* *Bracketed terms are optional extras as required.*

The shapes (profiles) seen in views down the flight path (top row of Table 1) are as follows:—

Round This shape was acquired from spherical or oblately spheroidal primary bodies. It requires some personal judgment. Arbitrary percentage differences in dimensions were discarded after trial. Weathered specimens may have distinctly unequal dimensions yet still be considered round forms.

Broad oval Forms having elongation (length/width) greater than one but less than or equal to four thirds. This is the definition of Fenner (1940: 312) re-stated in a form which emphasizes the importance of elongation related to rate of rotation as a basis for classification. Conventionally, length and width are the longer and shorter rectangular dimensions normal to the flight path and thickness is measured parallel to the flight path. Occasionally, as with some teardrop cores, thickness is greater than width and very rarely, greater than length. For round australites, diameter or range of diameter replaces length and width. For asymmetrical bodies, length may be inclined off the normal to the flight path, and more rarely, width also.

Narrow oval Forms having elongation greater than four thirds but less than or equal to two. Likewise from Fenner (1940).

Boat Forms having elongation greater than two but not having a waist. Also from Fenner (1940). The additional requirement that hoats should have more or less parallel sides is unnecessary. From measurements of about 650 oval australites and parallel-sided australites gleaned from several Western Australian collections, frequencies of elongation were plotted at intervals of 0.01 unit elongation and curves prepared (Fig. 2). With elongation increasing beyond 2, the frequency of occurrence of parallel sides soon equals oval shapes and then becomes dominant. Thus with the above definition, parallelism of the sides usually follows. Fenner's arbitrary definition coud not have been better choosen to reflect the critical rate of rotation above which previously convex sides became parallel. The acceptance of an arbitrary elongation factor precludes the need for personal judgment.

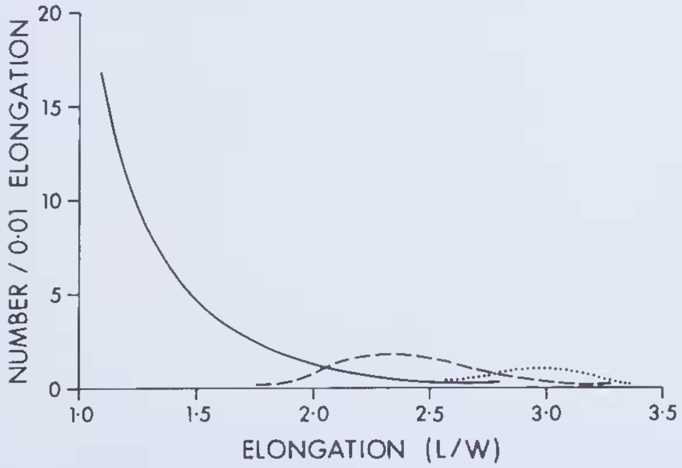


Figure 2.—Abundance curves of australites for a range of elongation. Oval australites—firm line. Parallel-sided australites—broken line. Dumbbells—dotted line.

Dumbbell Forms having a waist, however slight, and those in which a dip is detectable in the posterior elevational profile even if a waist is not detectable in plan view. The waist is affected by aerodynamic processes including loss of stress shell (Chapman 1964: 845) but this does not usually destroy the "saddle" form of the posterior profile which survives to indicate the former dumbbell shape.

Teardrop Forms developed as a primary process or sometimes by the separation of dumbbells during ablation flight, but excluding as broken dumbbells those formed on impact or during terrestrial weathering where the derivation is evident as a width of broken waist.

Canoes are generally listed with the above shapes. Their characteristics shape with thin extended ends, often pointed and often backwardly curved, is usually visible in plan view but only the body shape was inherited from the primary body: the ends consist of secondary glass. Canoes are treated in the next section with the other forms developed by secondary processes.

(b) Shape seen normal to the line of flight.

For australites in the conventional vertically downward flight path, these views are elevations. The terms side and end elevation were used by Baker (1972) but other terms such as side view, side or end aspect or end-on aspect have also heen used. The shapes usually include portion of the posterior surface of flight inherited from the primary body, and elsewhere the shape features developed by later processes. The aerodynamic effects and partly in consequence the terrestrial effects are closely linked to the sizes of the primary bodies which, for purposes of description, are defined as follows:—

large: spheres of diameter greater than about 30 mm and elongated bodies of similar thicknesses.

medium-sized: spheres of diameter about 10-30 mm and elongated bodies of a similar range of thickness.

small: spheres of diameter less than about 10 mm and elongated bodies of similar thicknesses.

The eight elevational shape types are shown in the first column of Table 1. They are detailed below.

Flanged form After ablation stripping of small and medium-sized bodies reached the stage that the leading edge encroached on the "equator" of the body, the primary surface behind the leading edge converged rearward instead of forward. Some of the melt stripped from the anterior surface was coiled into the eddy zone in the shelter of the leading edge to form a flange. So-called "small" flanged forms have relatively exaggerated flange width/core radius, generally 0.7-1.0, and the posterior pole of the core is at or below the level of the flange (Cleverly 1979b). Well preserved flanged forms are increasingly rare at higher elongations: few are more elongated than broad oval.

The largest primary body known to the writer to have developed a flange was a sphere 36 mm diameter. Usually a body of that size lost the stress shell spontaneously (Chapman 1964: 848) and with it the flange, leaving no evidence that a flange ever existed. Ideally, a further size category of "flange-forming" bodies might be recognised overlapping the lower range of the large "core-forming" bodies but large australites with convincing evidence of the former existence of flanges are so rare that the size limits of the category could not as present be defined.

Discs (round) and plates (elongated) Flanged forms developed from small primary bodies and having flange width/core radius usually greater than one and tending to infinity as flange developed at the expense of the remnant of primary body (Cleverly 1979b). Some of the shapes allowed for in the system are rare or unknown (Table 1). Very small bodies were secondarily heated throughout and do not therefore show any of the features associated with the highly heated surface layer of medium-sized and large australites which became the aerothermal stress shell. However, they may show shape modifications resulting from frontal collapse of the hot thinned glass or other kinds of failure by folding.

Bowls Small forms with obliquely backward development of secondary glass constituting the walls of the bowl (Cleverly 1979b). The remarks in the preceding paragraph regarding rarity or absence of certain shapes, lack of stress shell and susceptibility to folding apply also to bowls.

Canoes Characterized by thin, extended, secondary glass on the ends and named according to the shape of the body exclusive of that "flange". Canoes with round or teardrop bodies do not occur *i.e.* canoes did not develop from non-rotating parent masses. Canoes are envisaged as developing when elongated bodies encountered the earth's atmosphere with the axis of rotation very closely aligned with the flight path. In general, australite bodies in ablation flight were stable in pitch and yaw but not in roll (Chapman *et al.* 1962). The canoe parent bodies could have progressed like slowly rotating propellers, throwing secondary melt to the ends, the resulting end-flange growing increasingly backward if development continued into the stage of maximum deceleration. It is reiterated that when the axis of rotation was not very closely aligned with the flight path, rotation was damped out whilst the body settled into its flight orientation or was reduced to an axial wobble.

Indicators of the first type (indicators I) Australites of medium size which retain part of the flange of full width and part or all of the stress shell. They indicate the flanged form. The use of "indicator" here is an extension of the original meaning. Fenner (1935, Fig. 1) illustrated cores which had lost portion of the stress shell and referred to them later as indicators (Fenner 1940: 316), a usage retained for indicators II (see below). Indicators I (Fig. 3B, D) may be regarded as a developmental stage towards lens forms or cores.

Lens forms Developed from flanged forms by loss of flange but retaining the entire stress shell. Elongated lens forms have the typical biconvex lens shape in cross section *i.e.* as seen in end elevation. Irrespective of whether loss of flange occurred during ablation flight (Fenner 1938, Fig. 2) or later as a result of impact or terrestrial processes (the so-called "button cores"), only the term lens is used here. The two distinct origins of these forms and the tendency for the first type to be small are not questioned but what is doubted is that they can always be distinguished from each other. Further, the use of "core" for specimens still having a stress shell conflicts with the meaning given below. The secondary glass of canoes is readily reduced or lost during weathering: canoes thus pass into lens forms which are indistinguishable from those derived from flanged forms.

Flanges lost in ablation flight might have been entire at that time but those lost during weathering will generally have been detached piecemeal. As now found, nearly all are fragmented, the exceptions being rare round flanges, especially of the smaller buttons on which the flange forms a greater part of the australite and is more stoutly proportioned. No allowance has been made in the tabular system for detached flanges, not because they are rare, but because the allotted row would be empty except for round flanges the only ones known.

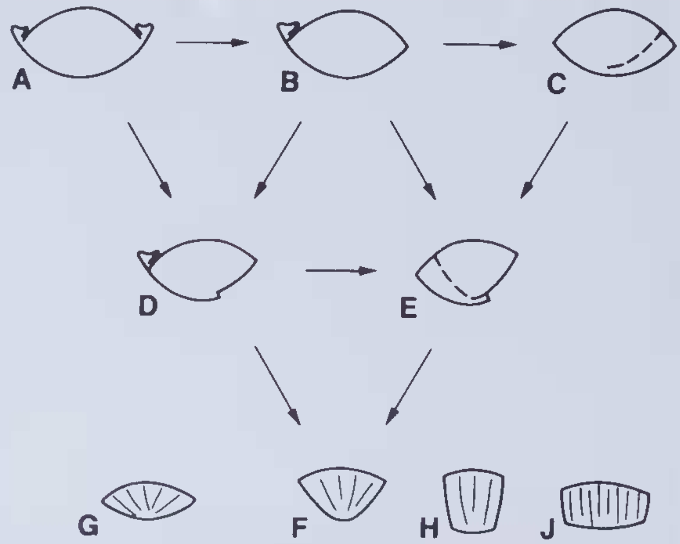


Figure 3.—Some possible sequences in the morphological series from flanged form to core. A. Flanged form. B. Indicator I. C. Lens form. D. Indicator I. E. Indicator II. F. Conical core with average apical angle. G. Shallow core with blunt apical angle. H. "Stopper" type core with gently tapering sides. J. "Small" core with sub-parallel sides and narrow scars in the equatorial zone.

Indicators of the second type (indicators II) Large or medium-sized australites which lack flange and retain only part of the stress shell. The large specimens indicate the shape of the secondary form at the end of ablation flight; medium-sized specimens indicate the lens form. The nomenclature of indicators and some developmental paths are shown in Fig. 3.

Cores The final forms of large and medium sized australites after complete loss of flange (if any) and stress shell. The largest primary bodies were not reduced by ablation stripping to the stage when a flange could form: they probably lost their stress shells spontaneously late in flight. It is rare to find a large body retaining part of the stress shell *i.e.* a large indicator II: for an example see Cleverly (1979a). With smaller bodies down through the medium range, loss of stress shell was increasingly dependent upon terrestrial processes, especially temperature changes. Cores formed from medium-sized australites tend to be bluntly or sharply conical with a remnant of the posterior surface as the base of the "cone", more gently anteriorly tapered "stopper" shapes, or almost parallel-sided "small" cores with narrow scars of detachment of the stress shell (Fig. 3F-J). Flight orientation of parallel-sided "small" cores is sometimes indeterminate. In analogous fashion, elongated cores tend to be bluntly or sharply wedged or tapered anteriorly: the end elevations are indistinguishable from the elevational views of the round cores. Badly abraded shallow cores may resemble lens forms but the angles between facets on the one and traces of flow ridges on the other usually enable a distinction to be made.

Additionally to the above, which account for 46 shape types and will usually accommodate about 90% of classifiable australites, the following two types are recognised.

Conical cores The shape of the posterior surface approximates a spherical triangle or spherical polygon. Detailed studies of the curvature of the posterior surfaces of 30 specimens show that they were derived from forms rarely as elongated as 4/3, the limit for broad oval. Instead of the loss of stress shell as a ring of uniform thickness, it has occurred as pieces of various and sometimes widely different plan view dimensions. The length and width of the remnant core are not generally parallel to or proportional to those dimensions in the parent form. It would be unrealistic therefore to classify these cores according to plan view dimensions, but their derivation from round and broad oval forms is evident. When the elongation was greater than c. 4/3, sufficient of the parent form usually survives for classification in the appropriate category according to the determined elongation.

Aberrant forms A variety of uncommon or rare shapes which do not fit neatly into the tabular classification but which usually constitute no more than about 4% of identifiable australites (Cleverly 1982a). In some instances the form has been influenced by instability of orientation, either consequent upon atmospheric encounter or resulting from changes in form during ablation flight. Rarely, the form can be seen as the result of fragmentation followed by further secondary shape generation (Cappadona 1981). However, in many instances the developmental histories and even the flight orientations of these forms are poorly understood if at all.

Morphology of Hampton Hill australites

A statement of the morphology of the Hampton Hill australites according to the above system is presented in Table 2. From that statement, information may be extracted for various purposes. Four such extracts are discussed below.

1. The general groups extracted from Table 2 are shown in Table 3. The four items are nominally equivalent to the following categories of Fenner (1940):—

   Group A
   Group B, Classes B1 and B2
   Group B, Class B3, sub-class B3a
   Group B, Class B3, sub-class B3b

The equivalence is indeed only nominal as may be seen by comparison with the Kennett collection from the arid South Australia-Northern Territory border which might be expected to show much the same percentage of classifiable specimens as Hampton Hill. The percentages are very different (Table 3) and the reasons not hard to

Table 2

Morphological classification and weights of australites from Hampton Hill, Station, W. A.

Shape type	Numbers of specimens			Weights of complete specimens		
	Complete	Broken	Total	Lightest g	Heaviest g	Mean g
Button	1	1	2	1.95	—	—
Disc	1	—	1	0.16	—	—
Round bowl	5	15	20	0.19	0.42	0.30
Round indicator I	49	6	55	0.13	4.92	2.01
Lens	2 463	1 244	3 707	0.11	4.86	0.88
Round indicator II	8	1	9	0.81	22.38	4.54
Round core	1 584	467	2 051	0.47	71.29	5.33
Flanged broad oval	1	—	1	2.31	—	—
Broad oval bowl	7	6	13	0.24	0.53	0.35
Broad oval canoe	4	5	9	0.97	1.43	1.20
Broad oval indicator I	1	—	1	3.43	—	—
Broad oval lens	298	69	367	0.14	4.74	1.13
Broad oval indicator II	1	—	1	3.48	—	—
Broad oval core	408	64	472	0.53	101.12	7.42
Flanged narrow oval	—	1	1	—	—	—
Narrow oval bowl	2	6	8	0.11	0.13	0.12
Narrow oval canoe	3	—	3	1.64	2.72	2.07
Narrow oval indicator I	1	—	1	0.92	—	—
Narrow oval lens	345	136	481	0.28	6.40	1.38
Narrow oval indicator II	2	—	2	2.31	4.15	3.23
Narrow oval core	289	86	375	0.93	69.25	6.74
Boat—canoe	1	2	3	2.85	—	—
Boat—lens	167	101	268	0.21	9.10	1.71
Boat—indicator II	6	—	6	3.61	6.10	4.80
Boat—core	142	67	209	1.06	42.00	8.30
Dumbbell—canoe	1	3	4	1.34	—	—
Dumbbell—indicator I	3	1	4	1.12	6.00	4.23
Dumbbell—lens	249	388	637	0.26	8.16	2.08
Dumbbell—indicator II	4	3	7	3.37	6.30	4.84
Dumbbell—core	113	135	248	1.11	47.00	9.02
Teardrop—indicator I	1	—	1	2.85	—	—
Teardrop—lens	224	54	278	0.13	5.79	1.44
Teardrop—core	57	4	61	1.30	15.15	4.86
Conical core	1 393	18	1 411	0.27	17.94	2.78
Abberant forms	159	37	196	0.39	23.41	2.68
	7 993	2 920	10 913		Mean	3.08
Fragments			10 773			
Flakes and flaked cores			241			
		Total	21927			

Table 3

General classification of australites from Hampton Hill Station compared with other localized samples

General classification	Hampton Hill Station, W.A.		S.A.—N.T. border (Fenner 1940)	Finke area (Cleverly unpub.)
	Number	Percent	Percent	Percent
Complete or essentially so	7 993 } 10 913	36.5 } 49.8	50.8 } 91.2	44.8 } 65.7
Incomplete but classifiable	2 920	13.3	40.4	20.9
Fragments	10 773	49.1	8.7	32.2
Flakes and flaked cores	241	1.1	0.1	2.1
Number of specimens	21 927		3 920	1 811

find. As an example, the "classified" sub-class B2a (Fenner 1940: Pl. VIII) consists of broken pieces of indicators II which might belong to any elongate group whatever: they would be unclassifiable in the more exacting system used here. The Finke collection from an adjoining area has been classified by the writer using the same system as for Hampton Hill, but this also shows considerable difference arising, at least partly, from the bias of the sample which is a chosen one sixth of the material offered for sale. The percentage of identifiable specimens is considerably inflated and the unidentifiable fraction correspondingly reduced.

2. A preliminary view of the state of weathering is possible from a consideration of the number of shape types present. Despite the large number of australites, only 35 of the 48 shape types are represented, the majority of them very poorly. Fourteen categories (6 lens form, 7 types of core and the aberrant group) account for 98.6% of the identifiable specimens. This reflects the severely weathered state of the material. These figures compare much more closely with the Finke collection which has 30 types represented, 14 of them accounting for 96.2% of identifiable specimens. The degree of weathering can be examined more conveniently by the method of item 4 below.

3. Figures may be extracted for plan or elevational view shaoes by adding the figures for individual items in the rows or columns of Table 1. The plan view shapes (Table 4) reflect in a general way the proportions of the primary bodies. Spheres are not distinguished from oblate spheroids and the shape proportions have been influenced by later events *e.g.* the separation of dumbbells during ablation flight. Having in mind the differences in definition for items ranging from broad oval to dumbbells and also canoes, adequate comparision with collections classified by other systems is not possible. Even a collection from Lake Yindarlgooda (Chalmers *et al.* 1976: 18) with the small percentage of canoes re-distributed proportionally shows values widely different from those found here (Table 4). Some difference from the biased Finke collection is not unexpected.

4. The elevational view shapes exclusive of aberrant specimens (Table 5) reflect especially the effects of aerodynamic and terrestrial shaping processes. When weathering is well advanced, as at Hampton Hill, it is convenient to group the frail types *viz.* flanged forms, discs and plates, bowls and canoes as a single item. The percentages of these and of those australites still in progress *via* indicators to a stable end form is extremely small. Almost all medium-sized specimens have reached what is probably a final stable lens form (mean weight 1.02 g) and almost all larger specimens have lost stress shells as the result of aerodynamic or terrestrial processes to reach a final stable core form (mean weight 4.96 g). Lens forms and cores comprise 96.8% of the Hampton Hill australites. In spite of the bias in selecting the better preserved material for the Finke collection, the same general trend is clearly observable (Table 5).

Table 4

Plan view shapes of australites from Hampton Hill Station and Finke, N.T.

Hampton Hill Station, W.A.				L. Yindarlgooda (Chalmers *et al.* 1976)	Finke, N.T. (Cleverly, unpub.)
Shape	Number	*Adjusted numbers	Percent	Percent	Percent
Round	5 845	7 074	66.0	50.5	71.8
Broad oval	864	1 046	9.8	21.6	8.8
Narrow oval	871	871	8.1		10.1
Boat	486	486	4.5	17.8	3.9
Dumbbell	900	900	8.4	7.4	4.6
Teardrop	340	340	3.2	2.7	0.8
Conical core	1 411	Re-distributed			
Aberrant	196	Eliminated			
No. of specimens	10 913	10 717	10 717	109	1 183

* Adjusted numbers and thence adjusted percentages are obtained by eliminating the aberrant forms and distributing the conical cores between round and broad oval groups in the proportions present in the original statement.

Table 5

Elevational shapes of australites from Hampton Hill Station, W.A. and Finke, N.T.

Elevational shape	Hampton Hill Station, W.A.		*Finke, N.T.
	Number	Percent	Percent
Flanged, disc and plate, bowl and canoe forms	65	0.6	2.5
Indicator I	62	0.6	8.3
Lens forms	5 738	53.6	49.4
Indicator II	25	0.2	3.1
Cores, including conical	4 827	45.0	36.7
Number of australites	10 717		1 183

*Cleverly, unpublished study

Lens forms and cores

The mean weights of the Hampton Hill lens forms increase with increasing elongation from round to dumbbell; the teardrop-lens also conforms if it is conceded that it formed from half the primary body and the mean weight should therefore be doubled. The cores, with one exception also show an increase (Table 6). The trend is present in the lenses of large samples from Earaheedy Station and Finke, N. T. but irregularly and imperfectly. The regularity of increase is best in the largest samples. The reason for the increase is unknown but it is advanced most tentatively that the reason is related to the progressive change in the ratio of cross-sectional area to volume (and mass) as elongation increases. This ratio could influence such variables as deceleration, heating and the expansion and contraction of the anterior shell.

Table 6

Mean weights of lens forms and cores

Shape type	Lens forms Hampton Hill Station, W.A. g	Cores Hampton Hill Station, W.A. g	Lens forms *Finke, N.T. g	Lens forms *Earaheedy Station, W.A. g
Round	0.88	5.33	1.78	1.30
Broad oval	1.13	7.42	1.99	1.57
Narrow oval	1.38	6.74	2.53	1.50
Boat	1.71	8.30	3.10	2.35
Dumbbell	2.08	9.02	2.66	2.11
Teardrop (x 2)	2.88	9.72	5.32	3.94
No. of specimens	3 746	3 986	347	259

*Cleverly, unpublished studies

Total and average weights

Total weight of 7 993 complete or essentially complete Hampton Hill australites ....24 616 g
Weight of 13 934 other specimens ....18 934 g
Total weight of 21 927 australites ....43 550 g

The mean weights calculated from the above are shown in Table 7. Such figures could be greatly influenced by the degree of care in collecting. Comparison is made in Table 7. with Myrtle Springs Station where australites are conspicuous against their background and the collecting was carefully done by a Museum party, the Port Campbell area, which was repeatedly carefully collected, and the Florieton area, a first amateur collection effort. Some authors omit either the mean weight of whole specimens or the mean weight of all specimens. The second of these, if small, is a guide to the reliability of the first. Without that reassurance it must be suspected that high mean weights could be artifacts of careless collecting or some other cause, such as the transport of australites (Cleverly 1976: 231).

Table 7

Mean weights of australites from Hampton Hill Station and other localities

	Hampton Hill Stn., W.A.	Myrtle Springs (Corbett 1967)	Port Campbell (Baker, 1956)	*Florieton, S.A. (Mawson 1958)
Number of complete australites	7 993	—	212	812
Mean weight of complete australites (g)	3.08	—	2.73	3.78
Total number of australites including fragments and flakes	21 927	175	573	1 475
Mean weight of all specimens (g)	1.99	1.25	**1.45	2.85

*Mean weights calculated from data of Mawson (1958) **Recalculated from data of Baker (1956)

Weight distribution

The Tillotson collections of located specimens are numerically large and have resulted from careful searching. They therefore provide a rare opportunity to study weight distribution in a large sample of whole australites. Forty three trays of australites provided from time to time by Mr R. G. Tillotson were accepted as a sample of the stack of trays. They contained 6165 australites of which 2157 were whole or essentially so. All whole specimens were weighed, the frequency of the weights in 0.01 g intervals plotted as a histogram and from it a curve drawn and smoothed slightly (Fig. 4).

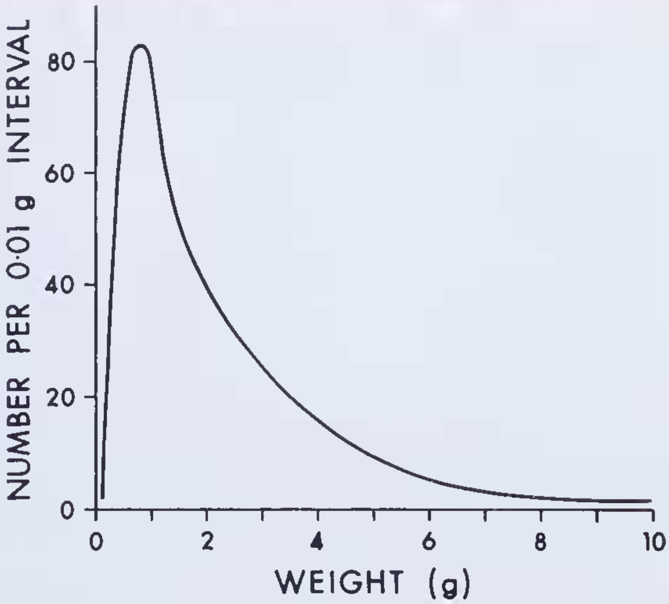


Figure 4.—Frequency of weights for 2 103 whole australites out of sample of 2 157. The balance of 54 had weights 10.01-58.25 g lying beyond the upper weight limit of the figure.

The mode is closely 0.9 g. Above that weight the frequency declines at first rapidly and then more slowly. There are 2103 specimens under the curve in Fig. 4. The remaining 54 specimens are decreasingly numerous between 10.01 and 58.25 g, *i.e.* over a width nearly five times that of the figure. This portion of the curve may reflect the primary event which scattered small molten masses having decreasing chances of holding together with large size. If so, the distribution has survived—at least in a general way—the rigors of reduction in size and re-shaping by aerodynamic and terrestrial processes. Several causes may have contributed to the form of the curve to the left of the mode. A minimum size of primary body is presumably needed if it is to survive atmospheric entry and leave a detectable secondary body. Weathering and erosion processes have reduced the sizes of most australites and perhaps destroyed some of the smallest ones. But the major difficulty is in observing small specimens in the field even for the most painstaking collectors. A common difficulty, that persons collecting for reward may ignore small specimens and flakes as being useless to lapidaries and therefore valueless does not apply to the collections used here.

The curve may be compared with that of Fenner (1934, Fig. 4), whose approach was radically different. Fenner used the average weights of those morpholigical groups having averages less than 3 g plotted in 0.2 g intervals to obtain a very irregular bimodal frequency distribution of 1858 specimens, and from that distribution a curve was drawn. Some of the groups may have included individuals with weights exceeding 3 g: on the other hand, excluded groups may have contained individuals with weights less than 3 g. The majority of specimens came from Israelite Bay (Fenner 1934: 65) which is about 370 km south-south-east of Hampton Hill Station. Despite the different approaches and localities, the resemblances between the curves are close. Both show modes of c. 0.8-0.9 g, a strongly concave frequency curve asymtotic to the weight axis for the higher weights and a slightly convex curve for weights below the mode *i.e.* plunging increasingly steeply as size decreases and detection becomes increasingly difficult.

Chemical composition and specific gravity

The analysis of an australite from Kurnalpi was given by Taylor (1962) and of a second from the same locality by Taylor and Sachs (1964): trace element data were included.

Analyses of a specimen from each of Lake Yindarlgooda and Lake Lapage were published by Chapman and Scheiber (1939) and allotted to the "normal" chemical type. The specific gravity of australites from the same two localities was studied by Chapman (1971, Figs. 4(d) and 5(b)) in samples of 912 from Lake Yindarlgooda and 1094 from Lake Lapage. The frequency diagrams show single, strongly pronounced modes (70%-80% of samples) in the 2.45-2.46 interval.

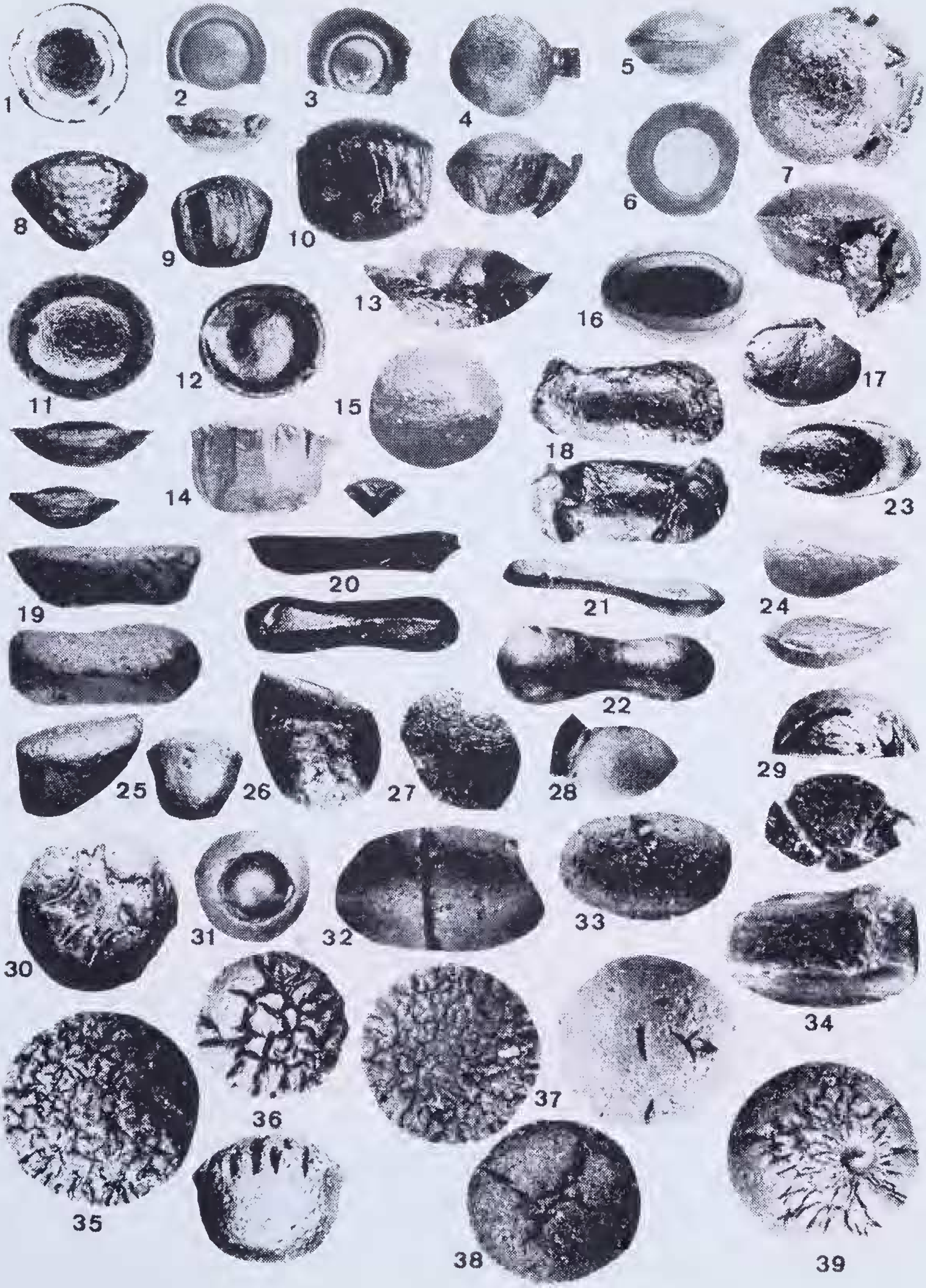
Mason (1979) studied a sample of 61 australites from Lake Yindarlgooda and found the specific gravities of 93% of them in the 2.45-2.46 interval: his three accompanying chemical analyses represent almost the whole range of specific gravity, or inversely, the range of silica content.

Individual specimens

Details have been published elsewhere of an exceptionally large broad oval core weighing 101.1 g found between Kurnalpi and Jubilee (Cleverly 1974), several small bowls (Cleverly 1979), a variety of aberrant forms (Cleverly 1982a) and hollow australites (Cleverly 1982b). A further variety of forms is shown in Fig. 5. They include two australites in the Tillotson collections found as weathered, well separated fragments which could be refitted together (Figs. 5.32 and 5.33). Refitting of fragments usually requires both careful search and good documentation before the possibility of reunion is recognised. Both circumstances are lacking for many Western Australian collections.

The most striking or the australites from Hampton Hill Station are those having patterns of V-grooves upon posterior surfaces, and occasionally, on anterior surfaces also (Figs. 5.35-39 and Fig. 6). Individual grooves are usually several millimetres long and not more than a millimetre deep. They may bifurcate but such grooves are seldom abundant (Fig. 6.1): no specimen shows a perfection of development like the core ftom Hattah, Vic. described by Baker (1973: 205 and Pl.28), though a closely comparable core is known from Western Australia (Simpson 1902: Pl.I). The grooves are especially common on larger cores but occur also on some lens and aberrant forms. Their pattern may be radial on round and broad oval cores and then increasingly longitudinal on the more elongated forms. The centre of radiation is most commonly the posterior pole but can be an eccentric feature such as a bubble cavity (Fig. 6.39). When a core has been broken early in its terrestrial history, grooves may radiate from a point within the remnant piece: a particularly fine example from elsewhere has been illustrated by Cleverly and Scrymgour (1979: Fig. 2.10). Grooves may be sufficiently numerous to form "bird track" or reticulated patterns, especially on round and broad oval cores, or on the other hand, so uncommon as to appear unsystematic, sometimes even a single groove.

Figure 5.—Australites from Hampton Hill Station, Western Australia, natural size unless otherwise stated. In elevational views, direction of flight is towards bottom of page. Abbreviations used are:— p.s. posterior surface, a.s. anterior surface and s.e. side elevation. 1. Button, p.s. with thin travertine coating. 2. Round indicator I, p.s. and below it, elevation seen through gap in flange. 3. Indicator I of "small" button, p.s., x 2. 4. Round indicator I, p.s. and s.e. below. 5. Lens, elevation, x 1.5 showing pale "flange band" posterior to rim. 6. Incomplete detached round flange, p.s., x 2. 7. Round indicator II, p.s., x 2 and s.e. below. 8. Round conical core, s.e., x 2. 9. "Small" round core, s.e. 10. "Small" round core, s.e. x 1.25. 11. Flanged broad oval, p.s. with side and end elevations below. 12. Broad oval bowl, p.s., x 2. 13. Broad oval canoe with "tortoise-shell" posterior surface, s.e., x 2. 14. "Small" broad oval core, s.e., x 1.5. 15. Wedged broad oval core, a.s. showing wedge, x 1.5. 16. Narrow oval lens, a.s. showing flow ridges. 17. Narrow oval lens with butt of flange, p.s. 18. Boat indicator II, p.s. above and a.s. below retaining small areas of stress shell at each end. 19. Wedged stout-waisted dumbbell core, s.e. above, a.s. below. 20. Dumbbell core, s.e. with a.s. below showing sharp wedge at right, blunter taper at left, triangular elevational view of wedged end above. 21. "Ladle" type dumbbell lens, s.e. as seen in vertically downward flight. 22. Asymmetrical dumbbell lens, a.s. showing worn transverse flow ridges. 23. Half of dumbbell canoe broken at waist, p.s. x 1.5. 24. Teardrop lens, p.s. and s.e. below. 25. Teardrop core, s.e. and end elevation. 26. Teardrop core, s.e. 27. Conical core, p.s. 28. Fragment of flanged form, p.s. showing saw-cut on junction between stress shell and the future conical core. 29. Broken lens, p.s. x 1.5 showing saw-cut on stress shell/core boundary; below, the broken surface of the lens showing the developing fragment of conical core. 30. Lens, p.s. x 2 showing crinkly top with U-grooves bordering the tongues of supposed overflowed melt. 31. Round hollow core, p.s. 32. Narrow oval core, p.s.. Found as worn separated pieces. 33. Narrow oval lens found as worn separated pieces. Identity of surface uncertain. 34. Folded plate form x 3.5. 35. Round core p.s. 36. Round core, p.s. above and s.e. below. 37. Round core, p.s. on left, a.s. on right. 38. Round core, p.s. 39. Round core, p.s. showing radiation of V-grooves from eccentric bubble cavity.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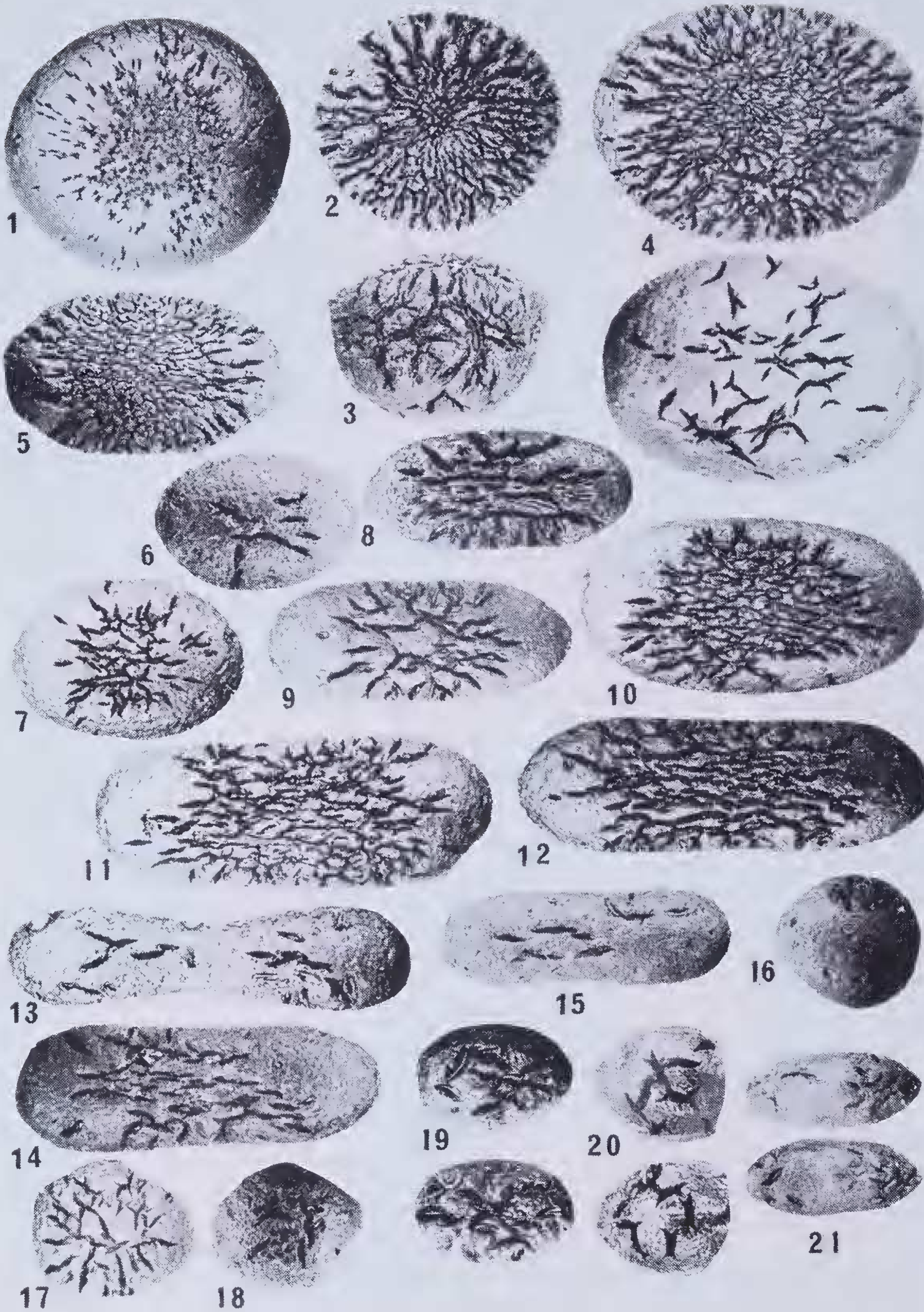
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On the several examples of cores having V-grooves on anterior surfaces (*i.e.* on surfaces created by loss of a stress shell) the grooves are fewer than on posterior surfaces and less systematic (compare the two views of each of Fig. 5.37 and Fig. 6.4). However, on three aberrant forms and a lens form which had not lost stress shells, grooves are about equally abundant on both major surfaces (Fig. 6.19-21).

In the writer's opinion, V-grooves and most other minor sculptural features are the result of terrestrial processes but their nature and location may be guided by residual strains from earlier events. V-grooves resemble tension cracks and are occasionally sigmoidal but their development could be aided by chemical or biochemical dissolution of the glass allowing grooves to gape as they were deepened. If residual strains do indeed concentrate the attack, then at least two sources of residual strain would be involved—the primary solidification for grooves on the posterior surfaces and the aerodynamic re-heating for grooves on anterior surfaces of flight. For grooves on the anterior surfaces of cores it would be necessary to postulate the retention of weakly strained glass after loss of stress shell; however, U-grooves are more usual upon such surfaces (Chapman 1964: 849 and Fig. 6.). Tension (or release) fractures would permit the surface to spread and the divided fractures would permit more immediate and localized extension. Such spreading is understandable for the posterior (primary) surfaces of bodies which have cooled from the outside inward and then lost portion of the outer shell but the writer is unable to suggest why expansion of other types of surface should also be necessary.

The Hampton Hill australites include several good examples of crinkly tops (Fenner 1934: 69, 1935: 31). Doubts have been expressed elsewhere that they could be formed by overflow of melt from the anterior surface and an alternative origin from radial grooves has been suggested (Cleverly 1982: 23 and Fig. 2T, U). In thin sections of two crinkly tops from Hampton Hill cut parallel to the line of flight, there was no detectable junction between the supposed "overflow" and posterior surface. An origin other than by overflow of secondary melt is thus indicated.

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Figure 6.—Australites from Hampton Hill Station, Western Australia. Except where otherwise stated, all views are posterior surfaces of cores showing V-grooves and are natural size. 1-2. Broad oval. 3. Side elevation of broad oval showing extension of groove system to anterior (lower) surface. 4. Narrow oval, upper view of posterior surface, lower of anterior surface. 5-7. Narrow ovals. 8-10. Boats. 11. Tapered boat. 12. Stout-waisted dumbbell. 13. Dumbbell. 14. Asymmetrical dumbbell. 15. Slightly assymmetrical, stout-waisted dumbbell. 16. Teardrop. 17-18. Conical cores. 19. Narrow oval lens, upper view the supposed anterior surface, lower the posterior surface. 20. Fragment of nut-like aberrant form, anterior surface above, posterior below. 21. The two major surfaces of a canoe-like aberrant form, flight orientation indeterminate.